Research on the distribution of superconducting currents in parallel circuits

Jiangao Zhang

Guangdong Basic Research Center of Excellence for Structure and Fundamental Interactions of Matter, Guangdong Provincial Key Laboratory of Quantum Engineering and Quantum Materials, School of Physics, South China Normal University, Guangzhou, 510006, China

Guangdong-Hong Kong Joint Laboratory of Quantum Matter, Frontier Research Institute for Physics, South China Normal University, Guangzhou, 510006, China

Abstract

In this research, a measurement system is designed capable of measuring the distribution of superconducting currents in parallel circuits. Hall effect detectors are used to measure the magnetic field excited by the current to determine the intensity of the current. The experimental results confirm that the distribution of superconducting current in parallel circuits is proportional to the inverse ratio of their inductances.

Keywords: superconductivity, hall sensor, parallel circuit, cuprate superconductors

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E-mail: zhangjiangao@m.scnu.edu.cn

1 Introduction

Since the discovery of superconductivity by H. K. Onnes[1] in 1911, research on superconductivity has been a hot topic in physics. Progress has been made in the search for new superconductors, such as copper oxide superconductors[2] , iron-based superconductors [3], and nickel-based superconductors [4]. Superconducting currents exhibit many novel properties different from those of currents in the normal state. In 1933, W. Meissner and R. Ochsenfeld [5] discovered the perfect diamagnetism of superconductors. In 1950, F. London [6] noted that the behavior of electrons in superconductors is a sign of collective motion. L. N. Cooper [7] proposed in 1956 that superconducting carriers are two electrons bound together in the form of Cooper pairs. Cooper pairs are equivalent to bosons, and many Cooper pairs form a Bose–Einstein condensation at low temperatures, resulting in collective motion behavior; thus, the superconducting current is a macroscopic quantum phenomenon. According to the Ginzburg–Landau [8] equation, the superconducting current is distributed on the surface of the superconductor. There are significant differences in the transmission properties between superconducting and normal-state currents.

In this study, an experimental system was designed to measure the distribution of current in parallel circuits formed by superconductors, and the rule governing the distribution of superconducting currents in parallel circuits was discussed.

2 Experimental preparation

2.1 Experimental principle

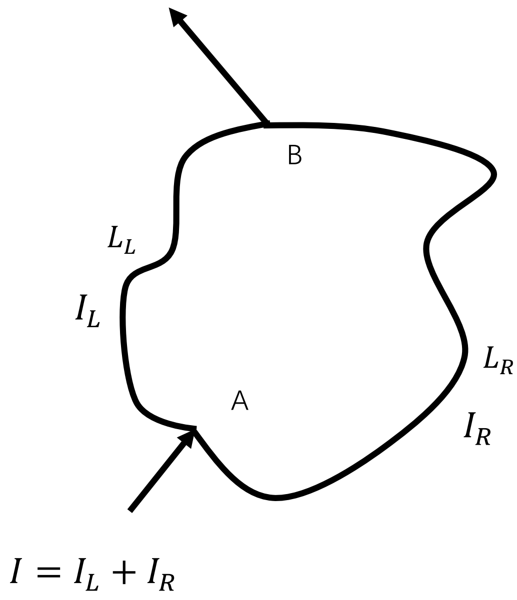

Fig. 1. A parallel circuit composed of superconductors. where L_L and L_R are inductances of the left and right paths, respectively.

A parallel circuit formed by the superconductor is shown in Figure 1, and the inductances of the two branches are L_L and L_R. If there is a current I flowing through the parallel circuits and splitting to I_L and I_R. The variation in magnetic flux generated by the currents I_L and I_R in the closed loop is $\Delta\Phi = L_L * I_L - L_R * I_R$. Owing to the electrodynamics of the superconductivity, the magnetic flux of the closed superconducting circuit is conserved, i.e., $\Delta\Phi = 0$, from which I_L/I_R=L_R/L_L [9]. The distribution of superconducting currents in parallel circuits is proportional to the inverse ratio of their inductances.

In this work, the rule I_L/I_R=L_R/L_L for the distribution of superconducting current in parallel circuits verified experimentally.

2.2 Preparation of samples

In accordance with the composition of $YBa_2Cu_3O_{7-\delta}$, a total of 40 grams of Y_2O_3, $BaCO_3$ and CuO raw materials were weighed, fully mixed, calcined at a temperature of 1133 K for 20 hours, removed and ground into powder, and two discs, each with a mass of 15 grams, were pressed out, sintered at 1203 K for 20 hours, and processed into two samples with dimensions, as shown in Figure 2.

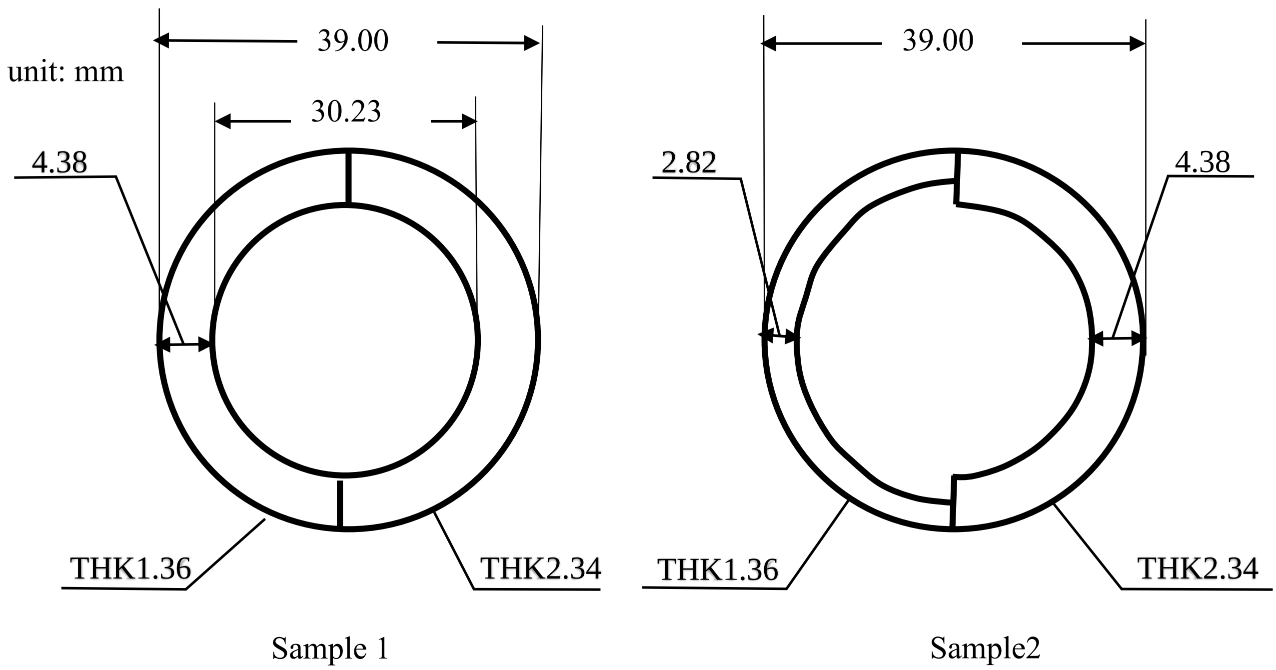

Fig. 2. Shape and size of the samples. THK denotes thickness

For both samples, the thickness of the left semicircle is 1.36 mm, and that of the right semicircle is 2.34 mm. Sample 1 has a loop width of 4.38 mm. For sample 2, the loop width on the left semicircle is 2.82 mm, and that on the right semicircle is 4.38 mm.

2.3 Installation of samples

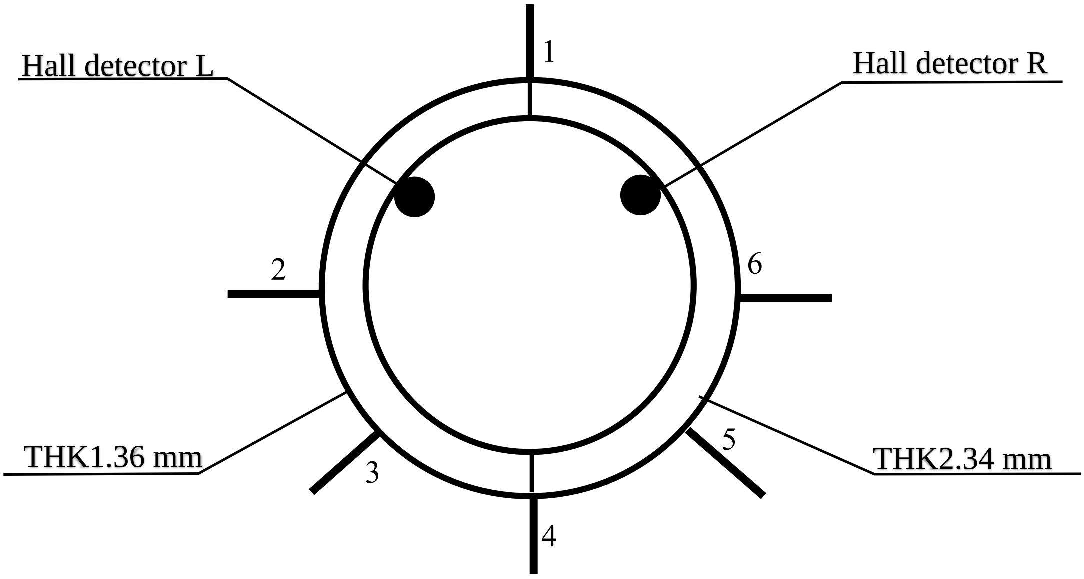

Fig. 3. Sketch of sample installation.

The installation of the sample is shown in Figure 3, with 6 electrodes and 2 Hall detectors (L and R) evenly spaced around the loop circuit. For both samples 1 and 2, the thickness of the left semicircle is 1.36 mm, and that of the right semicircle is 2.34 mm.

3 Experiments and analysis

3.1 Measurement of superconducting transition

The temperature of the superconducting transition for sample 1 was first measured. Sample 1 was installed according to Figure 3 and placed in a low-temperature environment. Electrodes 2 and 6 are connected to a constant current of 20 mA. The voltmeter is connected to electrodes 3 and 5 to form a

four-probe measuring system. As the temperature of the sample slowly decreased, the voltage between electrodes 3 and 5 varied, and the results are shown in Figure 4.

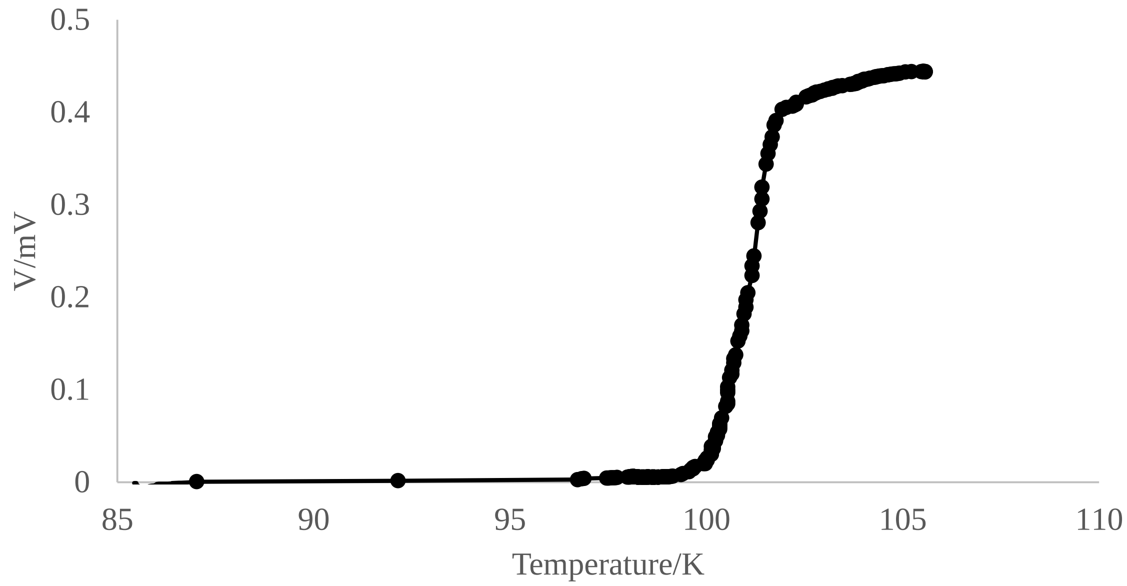

Fig. 4. The voltage between electrodes 3 and 5 varies with temperature.

The superconducting transition occurs at 102 K and is completed when the temperature is lowered to 98 K, reaching zero resistance.

3.2 Calibration of two Hall detectors

The temperature of the sample was lowered to 108 K. The sample was in a normal state at this temperature. A constant current of 180 mA is connected to electrodes 2 and 6. Under these conditions, two Hall detectors measure the same current, and the measured Hall voltages can be used to calibrate

the two Hall detectors.

3.3 Measurements and analysis

The 180 mA current was then connected between electrode 1 and one of any other electrodes. The variation in the Hall voltage was measured by changing the direction of the constant current. The measured Hall voltages are corrected by the calibration data. The ratio of the Hall voltage in the left semicircle to that in the right semicircle V_L/V_R is equal to the ratio of the current I_L/I_R.

The above calibration and measurement process was repeated at 90.5 K and a constant current of 100 mA. As shown in Figure 4, the sample is in a superconducting state at 90.5 K.

The results are shown in Figure 5.

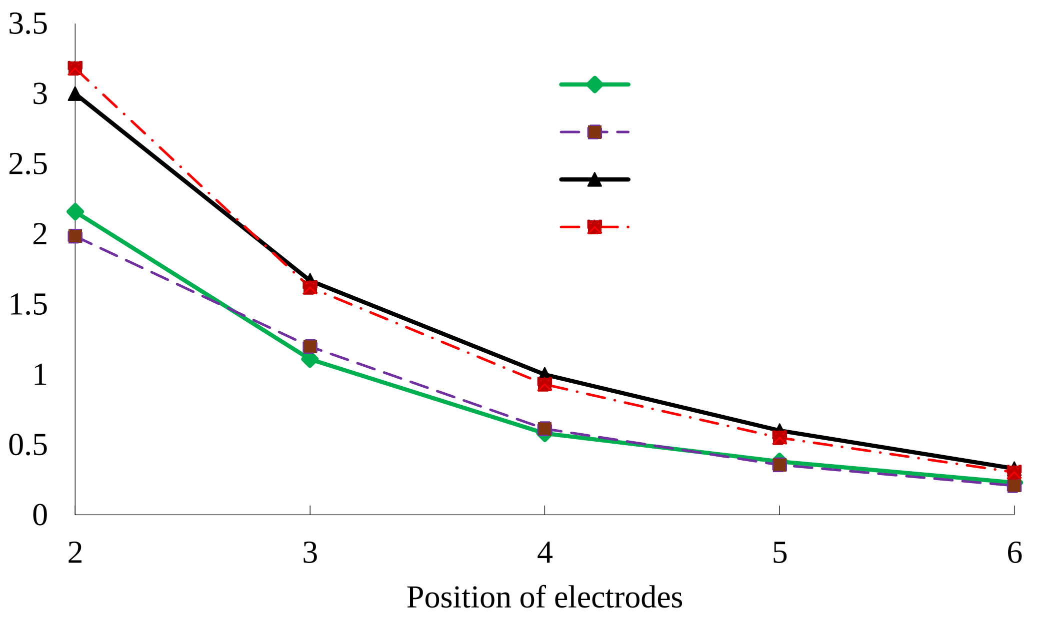

Fig. 5. Relationships of I_L/I_R (at temperatures of 108 K and 90.5 K, respectively), L_R/L_L and R_R/R_L with the position of the electrode. L_R/L_L and R_R/R_L (solid lines) are calculated according to the position of the electrodes. The two I_L/I_R lines (dotted lines) are the experimental data at temperatures of 108 K and 90.5 K, respectively. (The methods for calculating L_R/L_L and R_R/R_L are available in the Supplementary Information.)

As shown in Figure 5, I_L/I_R is consistent with R_R/R_L under normal conditions. In the superconducting state, I_L/I_R coincides with L_R/L_L, i.e., I_L/I_R=L_R/L_L.

The results of the measurements for sample 2 are shown in Figure 6.

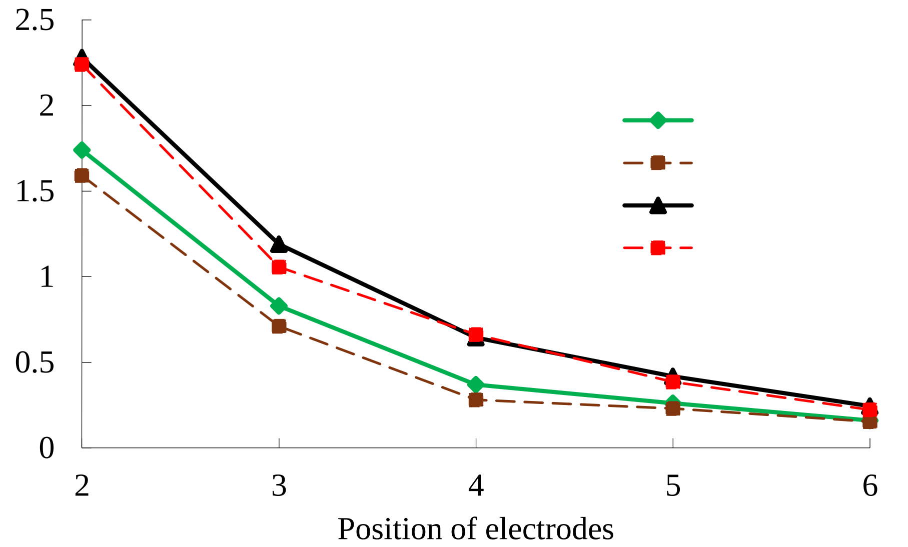

Fig. 6. Relationships of I_L/I_R (at temperatures of 109 K and 84 K, respectively), L_R/L_L and R_R/R_L

with the position of the electrode. L_R/L_L and R_R/R_L (solid lines) are calculated according to the position of the electrodes. The two I_L/I_R lines (dotted lines) are the experimental data at temperatures of 109 K and 84 K, respectively.

In Figure 6, I_L/I_R is consistent with R_R/R_L under normal conditions, and under the superconducting state, I_L/I_R is in agreement with L_R/L_L.

4 Summary

In this experiment, a measurement system was designed to measure the distribution of superconducting currents in parallel circuits.

The distribution of currents under normal conditions was measured, and the results are in agreement with the rule I_L/I_R=R_R/R_L; in accordance with Ohm's law, the designed measurement system is accurate and reliable.

Measurements of the two samples in the superconducting state show that the distribution of superconducting currents in the parallel circuits is proportional to the inverse ratio of their inductance, i.e., I_L/I_R=L_R/L_L.

The product of the current and inductance IL in parallel circuits composed of a superconductor is analogous to IR in the normal state.

5 References

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Supplementary Information is available for this paper.

Correspondence and requests for materials should be addressed to Zhang, J.G. E-mail: zhangjiangao@m.scnu.edu.cn